Electrically Driven Warm Dense Matter Experiments

P. Renaudin

Département de Physique Théorique et Appliquée
CEA, Bruyères-le-Châtel, France

with contributions of

C. Blancard, J. Clérouin, G. Faussurier, P. Noiret, V. Recoules
CEA Bruyères-le-Châtel

V. Korobenko, A. Rakhel
Joint Institute for High Temperatures, Moscou

Warm Dense Matter Winter School
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Outline

- Microsecond resolution techniques were pioneered by Lebedev and co-workers at the Institute for High Temperatures in Moscow, as an outgrowth of exploding wire studies

- Recent motivations appear with first WDM experiments

- Electrically driven WDM experiments are now performed in several laboratories

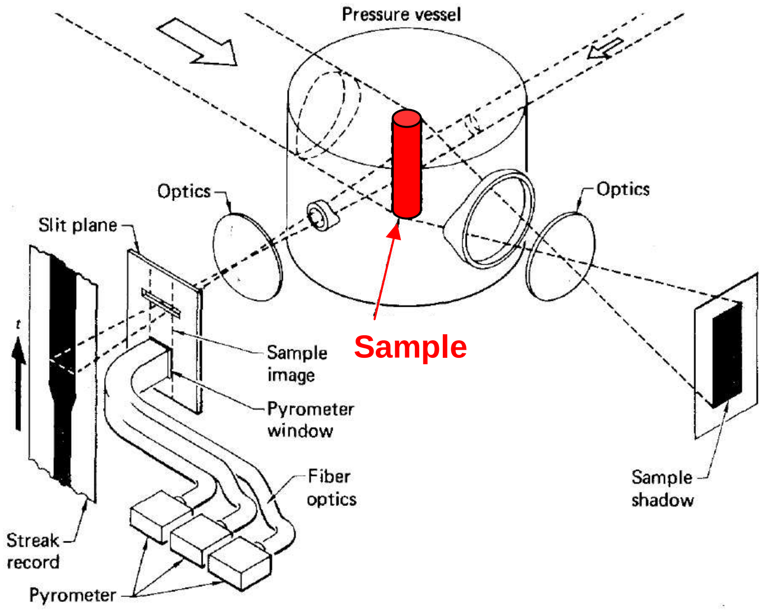
- Some illustrations from recent experiments performed at JIHT Moscou and CEA Bruyères-le-Châtel

Using fast transient methods allowed to measure thermophysical properties of hot liquids

Need to build and validate a global equation-of-state

Isobaric Expansion Experiments at LLNL used a pressure cell capable to hold rare gas at 0.4 GPa

Gathers, Int. Journal of Thermophys. 11 (1990)



Gathers *et al*., Phys. Rev. Lett. 33 (1974)

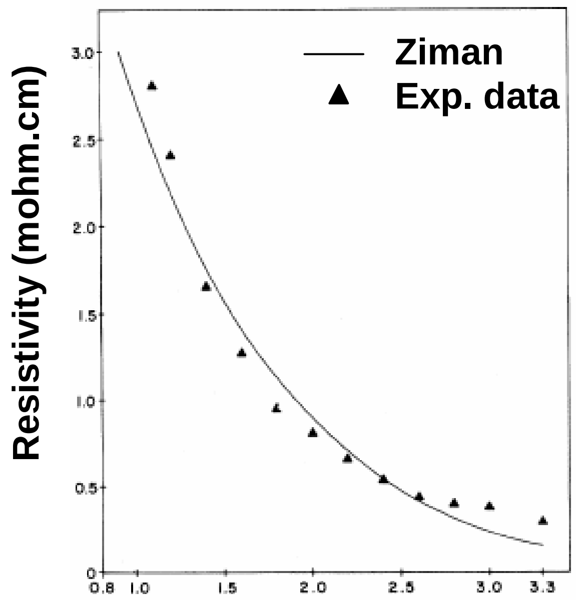
- **Rod samples are heated by current from a capacitor bank**
- **Current, voltage, sample cross section, and temperature are measured as function of time**
- **The EOS data are the pressure, volume, and enthalpy of the hot liquid (temperature up to 9000 K)**
- **The enthalpy-vs-volume isobars allow to adjust a « soft-sphere » model used to build the SESAME tables**

Transport phenomena in liquid metals were studied in exploding-wire experiments

« The Ziman theory of transport properties for liquid metals is remarkably successful when both the interference function and the electron-ion interaction are known »

Ashcroft & Lekner, Phys. Rev. 145, 83 (1966)

Liquid-copper resistivity



Ionic density (10^{22} cm^{-3})

- **Resistance can be measured** from the time-resolved electrical parameters of the circuit

- **Density can be measured** from the time-resolved measurements of the wire radii found by x-ray or optical shadowgraphs

Ben-Yosef & Rubin, Phys. Rev. Lett. 23, 289 (1969)

Confined exploding-wire experiments allow exploration of the WDM

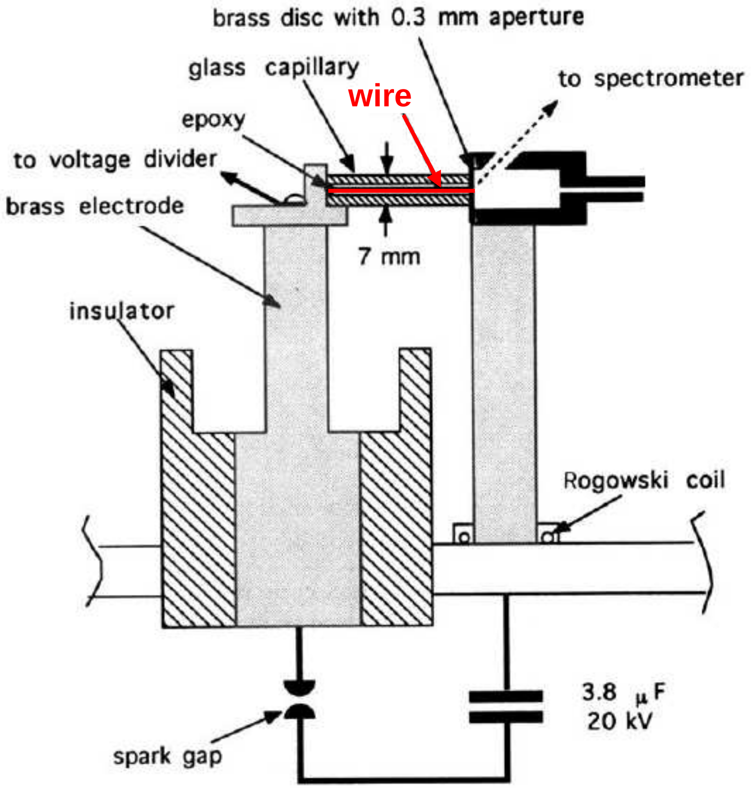
« The capillary confines the plasma in a uniform and measurable volume for a short time, during which it is possible to make accurate measurements of the conductivity, density and input energy, and to make good estimates of the temperature & pressure »

DeSilva & Kunze, Phys. Rev. E 49, 4448 (1994)

In the case of unconfined wire:

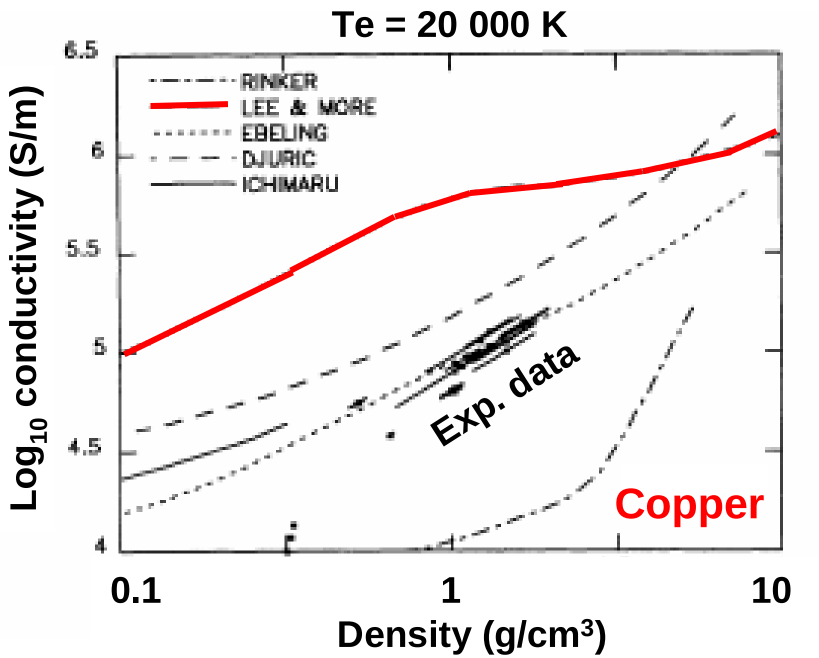
- **The density of the plasma is ill-defined, making precise measurements difficult**
- **Instabilities tend to produce axially nonuniform plasma, making interpretation of resistance measurements in terms of resistivity uncertain**

***Exploding Wires*, edited by W. Chace & H. Moore (Plenum Press, New-York, 1959)**

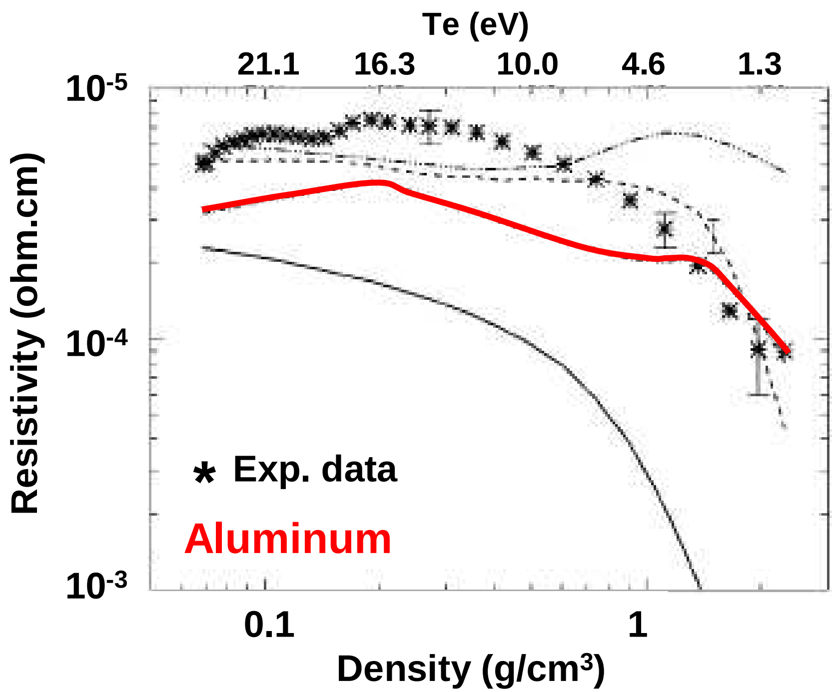


Models are questionable in the WDM regime

DeSilva & Kunze, Phys. Rev. E 49 (1994)



Benage *et al*., Phys. Rev. Lett. 83 (1999)

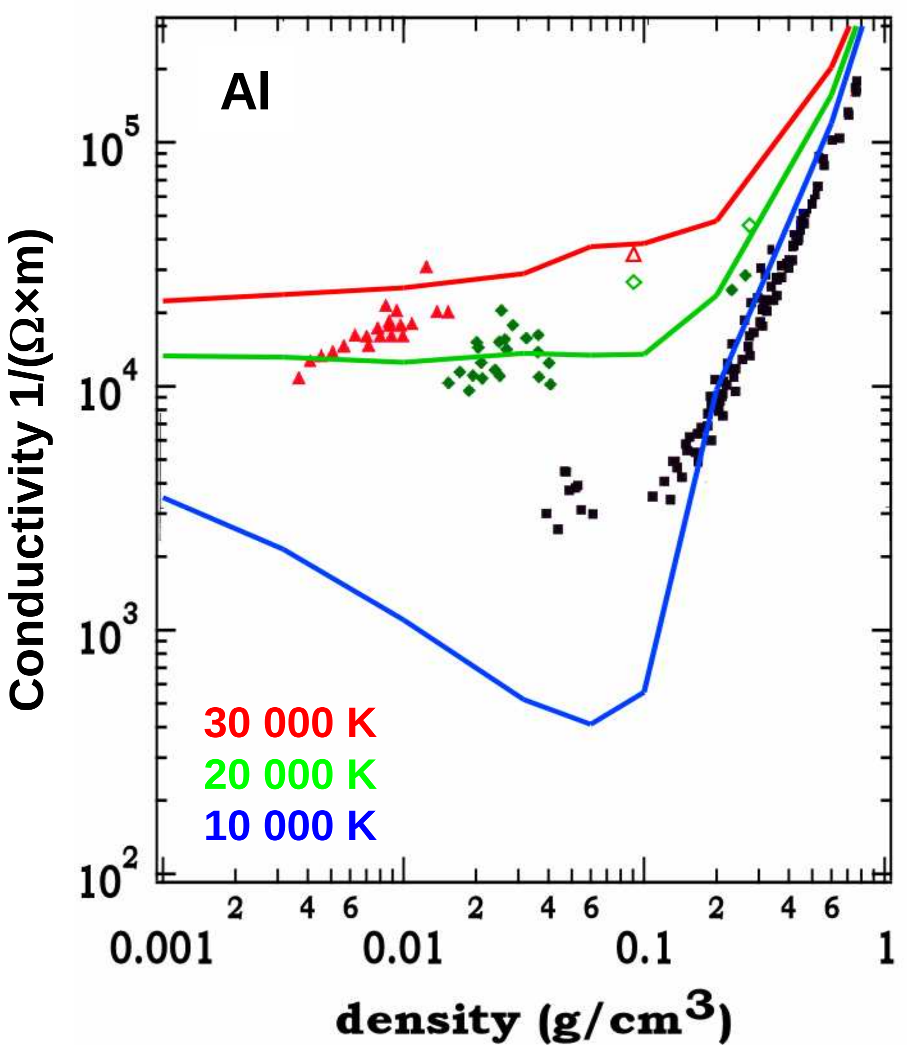


- Large discrepancies between models
- Lee-More model disagrees more than expected with the experimental data ?

Lee-More model: Drude formula
+ Effects of magnetic field
+ Dense plasma rules for log(Λ)
+ Minimum mean-free-path

Lee & More, Phys. Fluids 27 (1984)

Effects of the density on the electrical conductivity



DeSilva *et al*. (■) *vs* Ziman formula in average atom model

At low density ionization is driven by temperature

At low T a minimum of conductivity indicates where the ionization is driven by the density

A. W. DeSilva et al., Phys. Rev. E (1998)

Several laboratories now study conductivity of metals at few eV temperatures

Electrically Driven WDM Experiments

• Benage *et al*., LANL Los Alamos	Phys. Rev. Lett. 83 (1999) Physics of Plasmas 7 (2000)
• DeSilva *et al*., University of Maryland	Phys. Rev. E 57 (1998)
• Kunze *et al*., Ruhr-Universität Bochum	Phys. Rev. E 58 (1998)
• Renaudin *et al*., CEA bruyères-le-Châtel	Phys. Rev. Lett. 88 (2002) Phys. Rev. B. 76 (2007)
• Korobenko *et al*., JIHT Moscow	Phys. Rev. B 71 (2005) Phys. Rev. B 75 (2007)
• Grinenko *et al*., Physics Dpt. Haifa	Phys. Rev. E 72 (2005)
• Kim *et al*., Agency for Defense Dev., Korea	EPS Conf. Plasma Phys. (2006)
• Hasegawa *et al.,* Tokyo Inst. of Technology	NIMP Research A 577 (2007)
• Sasaki *et al.,* Tokyo Inst. of Technology	NIMP Research A 577 (2007)

In the WDM regime, each material is unique and many parameters are important

How to ensure homogeneous heating of a sample undergoing transition from standard into a high-Te state ?

The non-homogeneities are mainly caused by:

- Pinch-effect
- Inertia of the sample when the heating power changes rapidly

For the sample and vessel geometry:

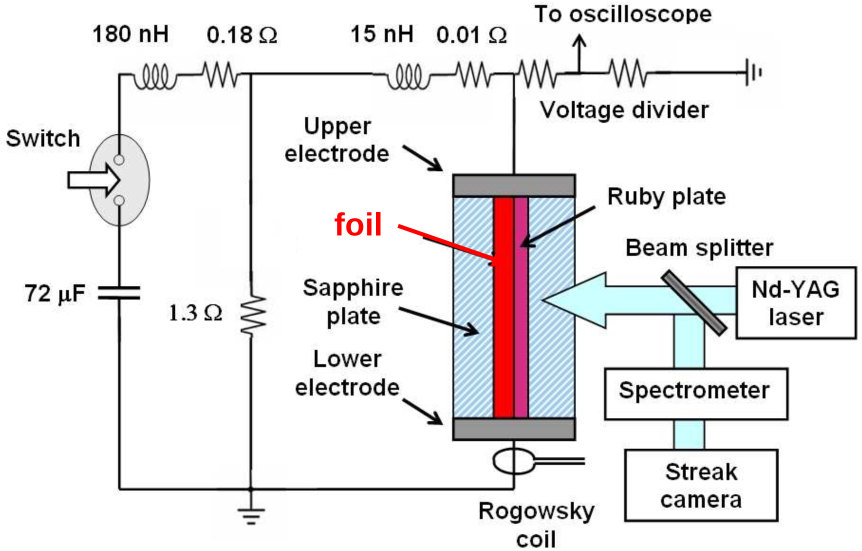
- Control of the viscosity, heat conduction and radiation
- Local thermodynamic equilibrium
- Displacement currents as low as possible
- Control of the interface between the sample and the confinement walls (no pollution!)

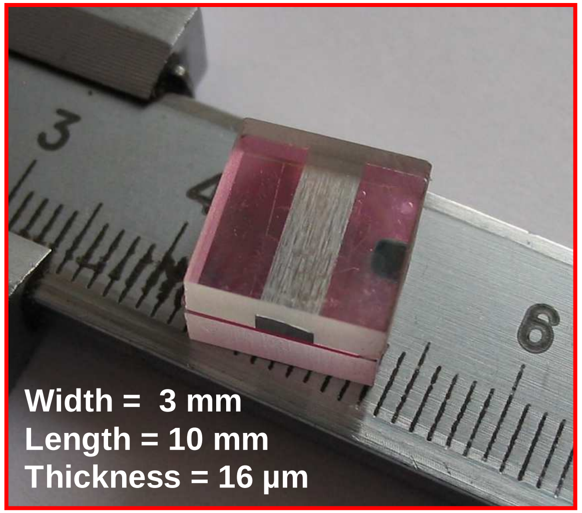
For the driver:

- Magnetic field strength at the sample surface as low as possible
- Quasi-stationary heating current

In Korobenko experiment a foil strip is confined by two polished sapphire plates

Typical confined experiment





- **1D MHD simulations of the heating dynamic are able to specify parameters of the experiment to approach a sufficiently homogeneous heating and reach the desired pressure range**
- **Measurements are performed during t<2 µs so that the main wave reflected from the free side surfaces of the experimental assembly does not disturb the sample**

Korobenko *et al.*, Phys. Rev. B 71 (2005)

In CEA experiment a homogeneous and thermally equilibrated plasma is created in an isochoric closed-vessel

- **EPI combines 2 techniques:**
  a slow high-pulse power bank
  and a high-pressure closed-vessel

- **The characteristic time of the pulse-power supply (100 µs)**
  - is long enough to allow the formation of a homogeneous plasma
  - is short enough to limit the effects of the wall ablation

- **Since the plasma is homogeneous, average density of the plasma is equal to** $\overline{\rho} = \frac{m}{V_{EPI}}$ **with V_{EPI} ~ 20 cm^3**

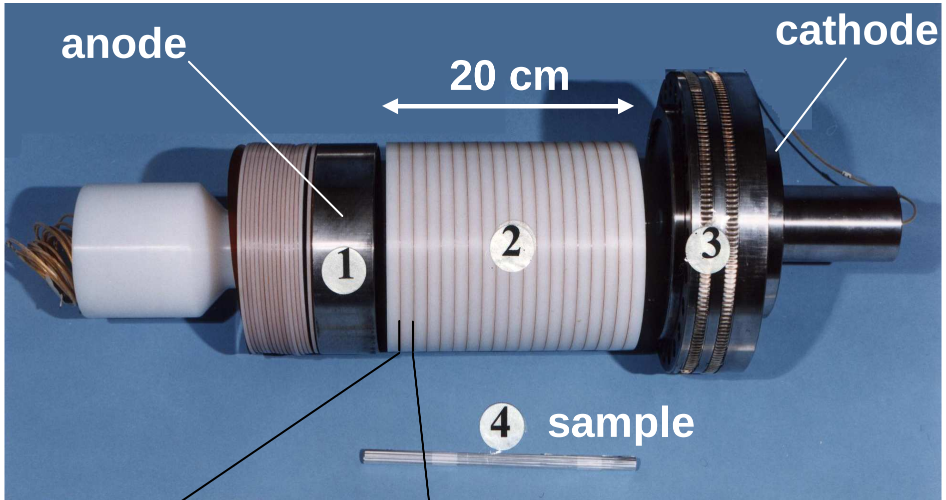
- **During each experiment, pressure, internal energy variation, mass density, and electrical resistivity are simultaneously measured with a precision of +/- 10%**

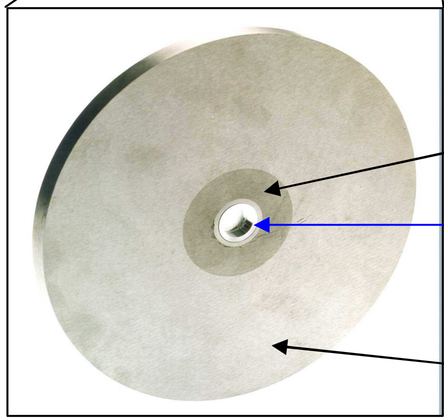
Plasma confinement is ensured by an alternate stack of high-pressure rings and insulator Kapton foils

Achieving a homogeneous heating:

- Quasi-stationary discharge
- Free-electrical arc diameter two times greater than the vessel diameter
- Skin-depth of an equivalent conductor six times greater than the vessel diameter
- Magnetic pressure created by a 100-kA current in a 12-mm conductor is ~30 MPa (<< plasma pressure)

Transverse radiography and 1D MHD simulations of the heating dynamic show a sufficiently homogeneous heating





1-cm-thick autofrettaged bimetallic rings

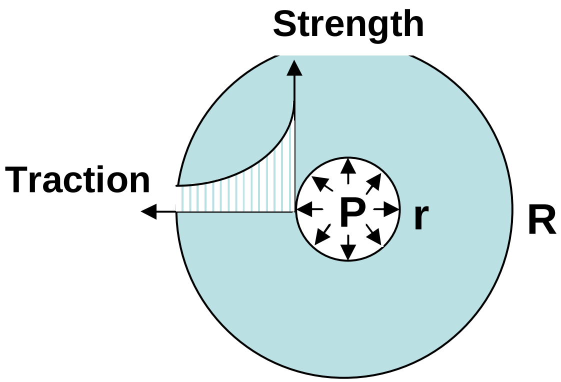
CWCo

A 12-mm diameter sapphire ring is bound in the center of each ring

Steel

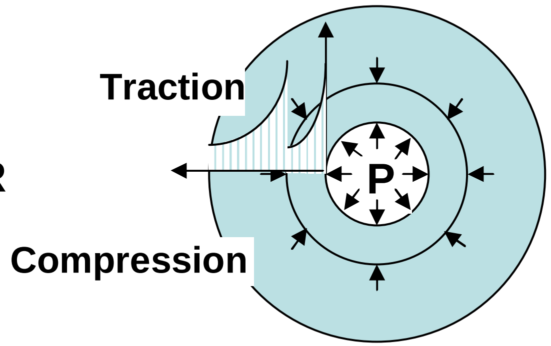
Principle of the frettaged ring

Steel ring	Autofrettaged steel ring	Autofrettaged CWCo ring
P<1 GPa	P<2 GPa	P<8 GPa



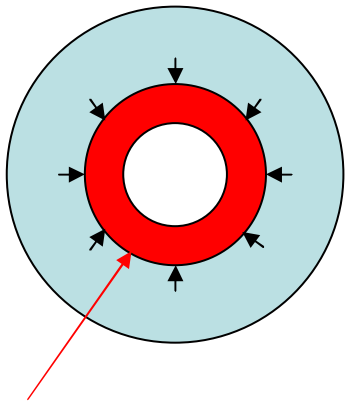
$$P < \frac{R_e}{2}\left[1 - \left(\frac{r}{R}\right)^2\right]$$

R_e = Elastic limit



Limitation

Material residual constraint in the internal ring



CWCo with a high-limit of compressibility

Principle of the frettaged ring

The maximal pressure is limited by :

- **the applied axial clamping force**
- **the sliding friction coefficient of the Kapton foil**

During the final mounting of the vessel,

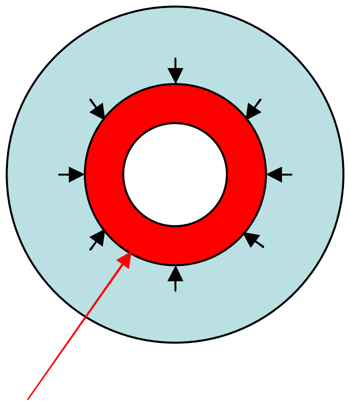
This axial force is set to 120 to 150 tons

The rigidity of the vessel at P=2.5 GPa is

$$2\frac{\Delta r}{r} = \frac{\Delta V}{V} = 2\%$$

Autofrettaged CWCo ring

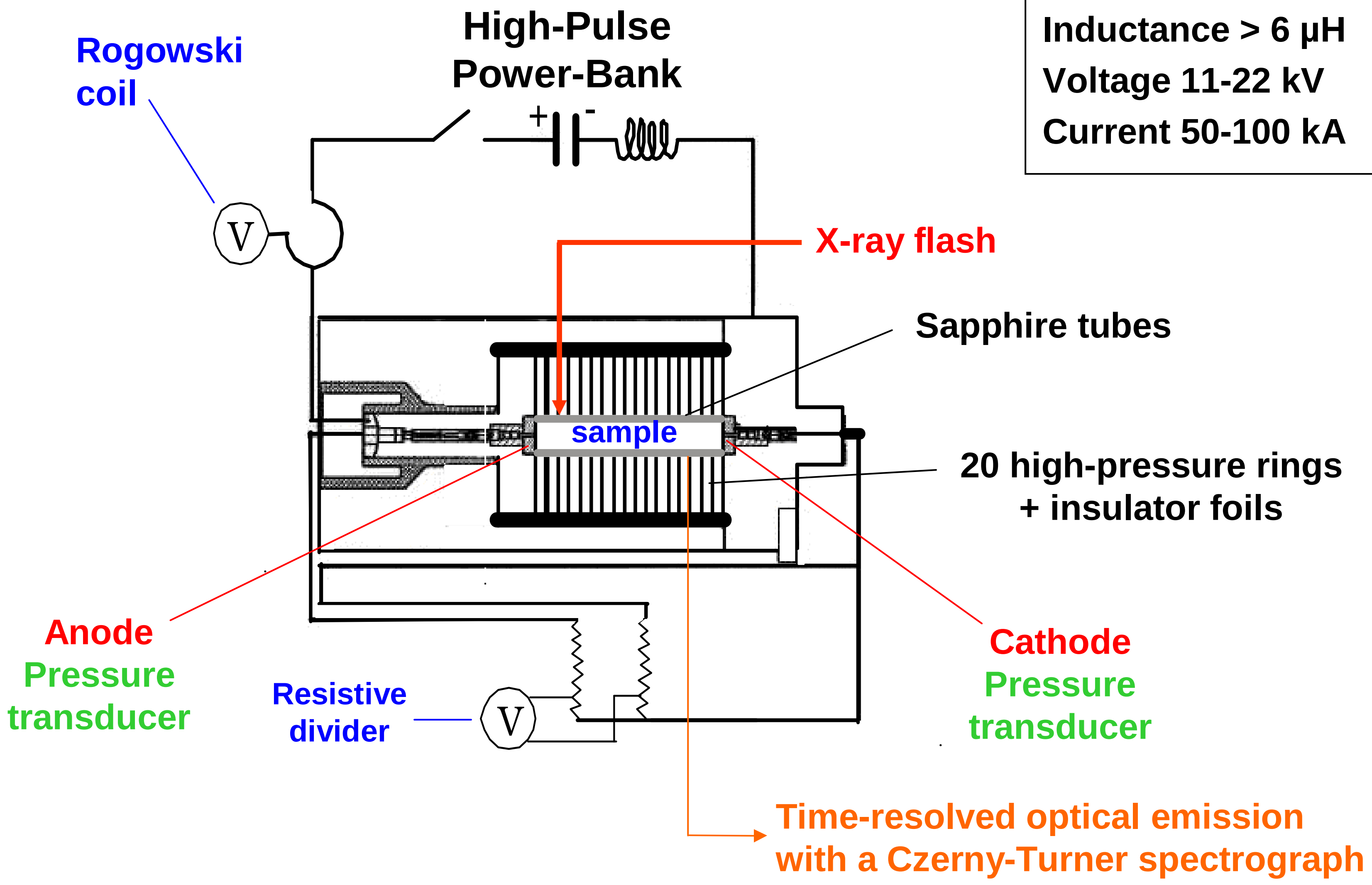
P<8 GPa



CWCo with a high-limit of compressibility

A long heating of the sample is driven by a slow high-pulse power-bank with 4 capacitors connected in parallel

Capacity < 4 mF
Inductance > 6 µH
Voltage 11-22 kV
Current 50-100 kA



Direct plasma measurements:
case of aluminum at a homogeneous density of 0.1 g/cm^3

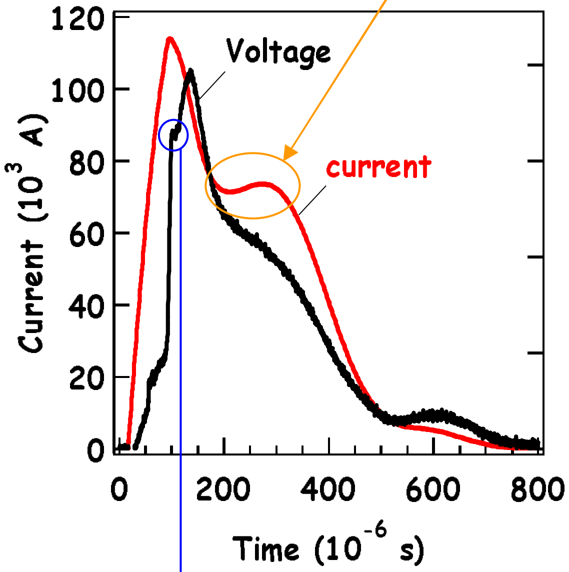
Voltage & current

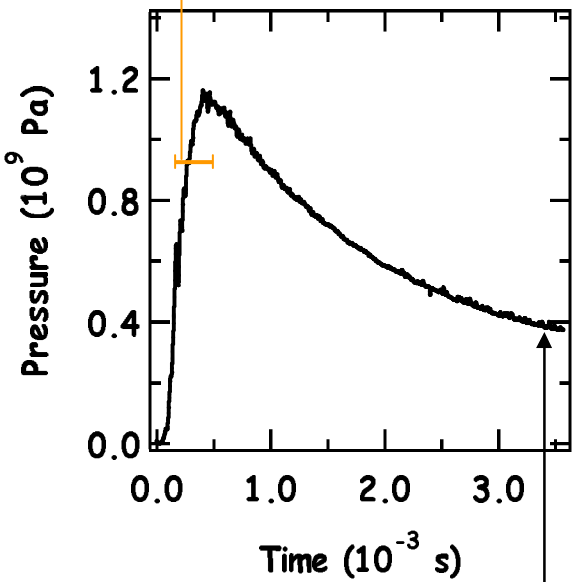
Pressure

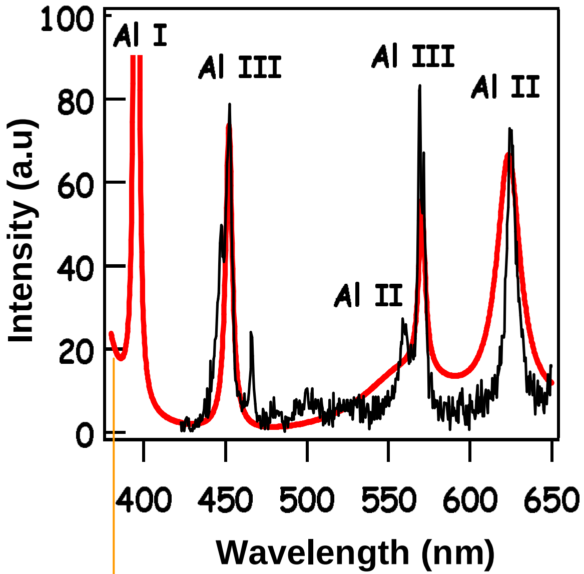
Optical emission

Arc regime induced by vapor ionization

Homogeneous plasma phase during 200 µs







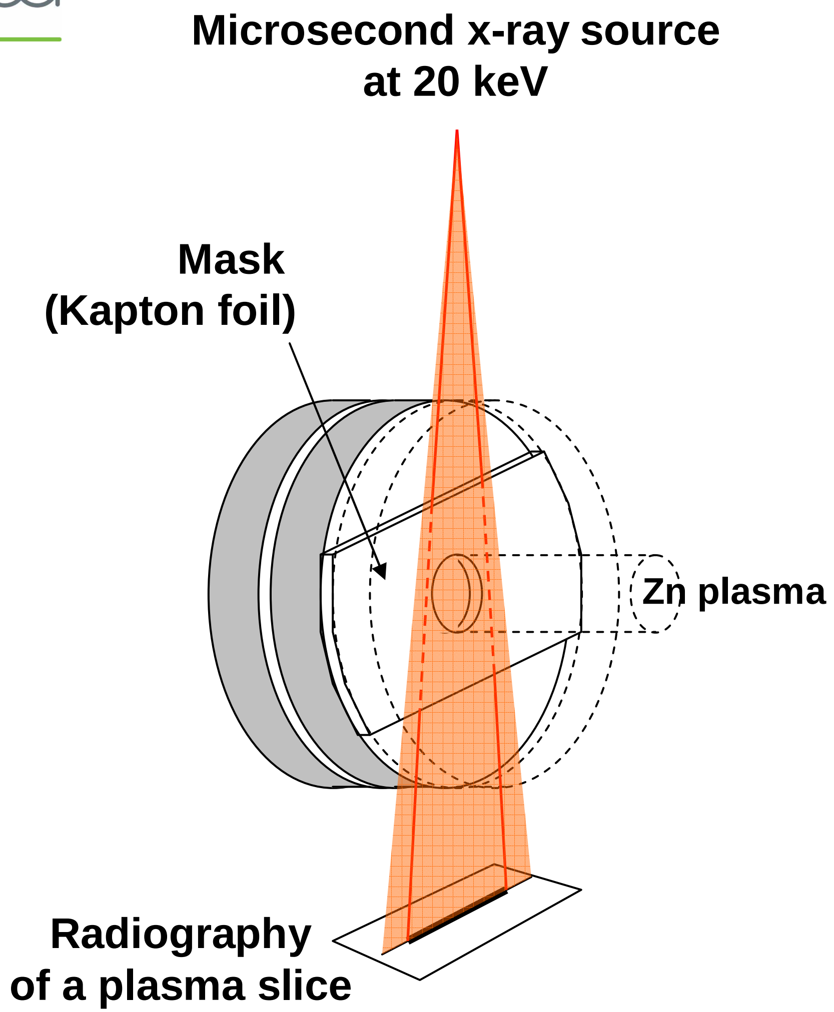
Luminescent discharge

Slow decay

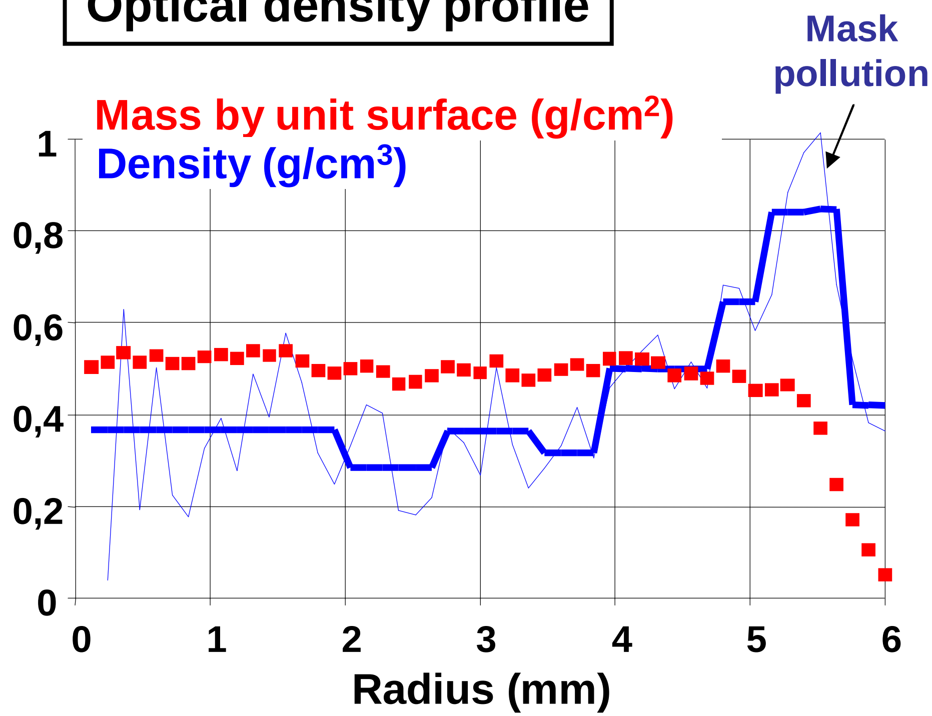
Modelling from Saha equilibrium

Luminescent discharge
20 000 K - 5.10^{18} cm^{-3}

Radial density distribution is measured by x-ray shadowgraphy



Optical density profile

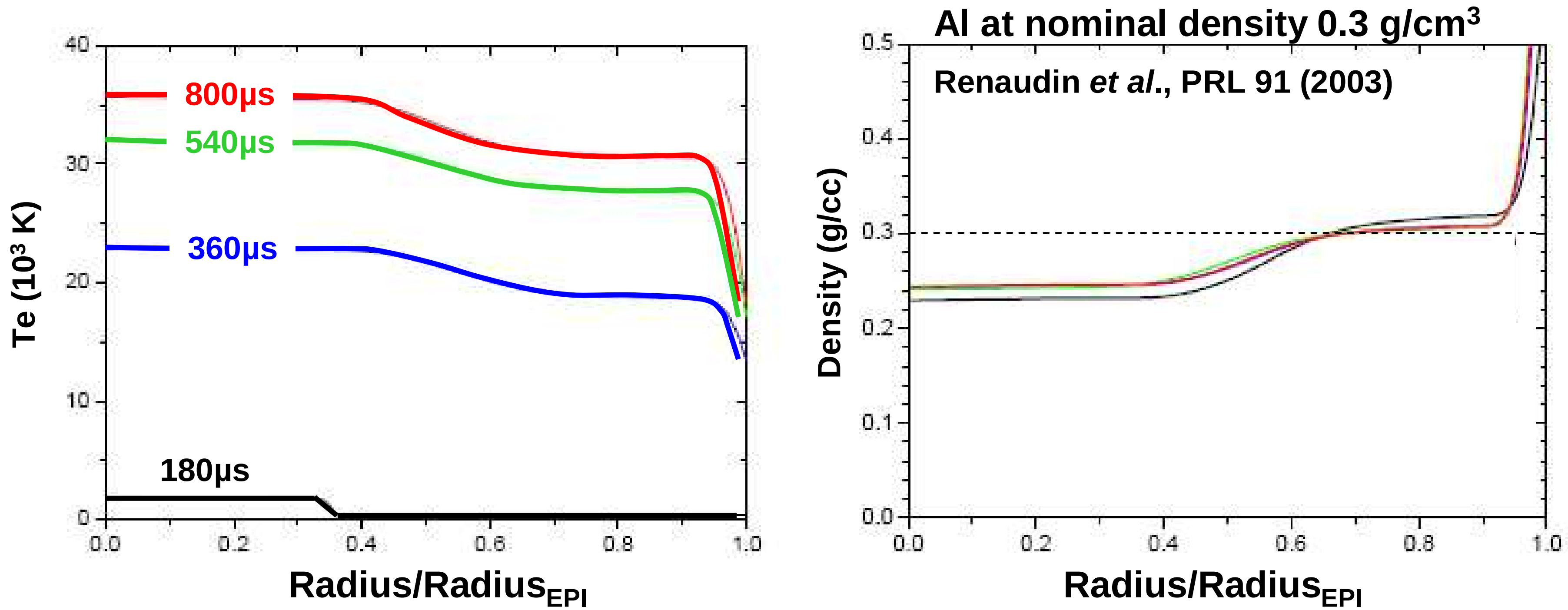


- The peak of density near the sapphire wall may be due to the accumulation of underheated vapour (state between the binodal and the spinodal lines)
- A good transverse homogeneity is achieved elsewhere

MHD simulations of the heating dynamic indicate that a homogeneous heating is achieved in EPI

1D MHD calculations performed by Rakhel (JIHT Moscow)

- Equations of motion with planar symmetry
- Maxwell equations, Ohm law and Lorentz relations
- No effects of viscosity
- Local Thermodynamic Equilibrium
- No displacement currents
- The circuit producing the heating current pulse is stationary

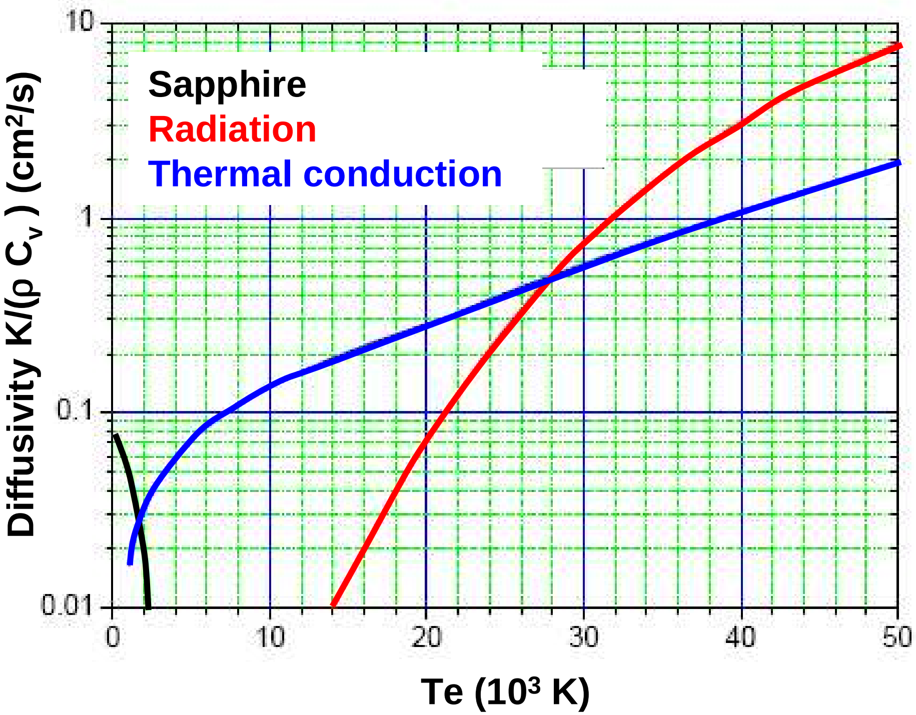


Energy loss due to thermal conduction and radiation heat transfer through the EPI walls is small

Heat conduction equation assuming that skin-effects plays no role (E field is homogeneously distributed across the plasma)

$$\rho c_V \frac{\partial T}{\partial t} = jE + \frac{1}{r}\frac{\partial}{\partial r}\left(r\kappa_{tot}\frac{\partial T}{\partial r}\right)$$

C_V constant volume specific heat capacity
K_{tot} total thermal conductivity coefficient (thermal conduction + radiation)



EPI experiment (Al 0.1 g/cm^3)

- **Electronic conduction assuming the validity of the Wiedemann-Franz law**
- **Radiation heat transfer assuming gray-body approximation using mean Rosseland opacities from SESAME**
- **Thermophysical properties of sapphire taken from Russian data**

Rakhel, Private communication

Experimental data of ΔU_{int} are inferred assuming thermal losses are radiative during the plasma phase

$$\Delta U_{int} = (E_{el} - E_{rad}) + \Delta W$$

Internal energy variation

Input energy

Thermal losses at the wall

Mechanical work due to the vessel expansion under pressure

Radiation (Planck)

$< 1\% \ E_{el}$

$$\frac{dU_{int}}{dt} = \frac{dE_{el}}{dt} - \alpha \times S_0 \times \sigma \times T(U_{int})^4$$

α is measured

Plasma surface

$T=f(U_{int})$ using SESAME tables or other models

Monophasic evolution along an isochore

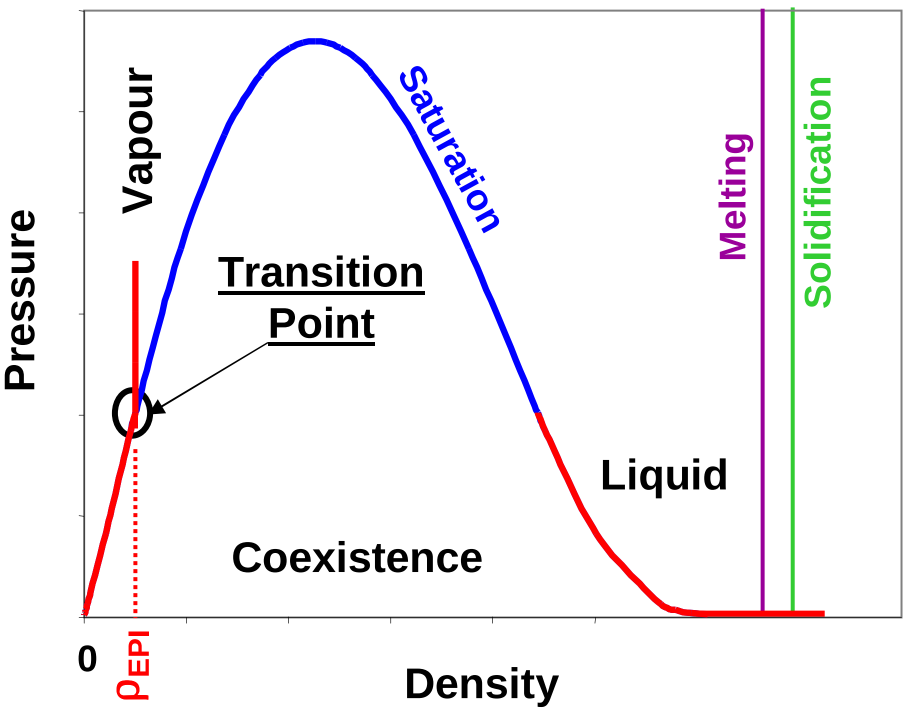
$\frac{dU_{int}}{dt} = 0$ When pressure and conductivity are maximal

The sample goes from the solid state to a known average density plasma through a two-phase liquid-gas region

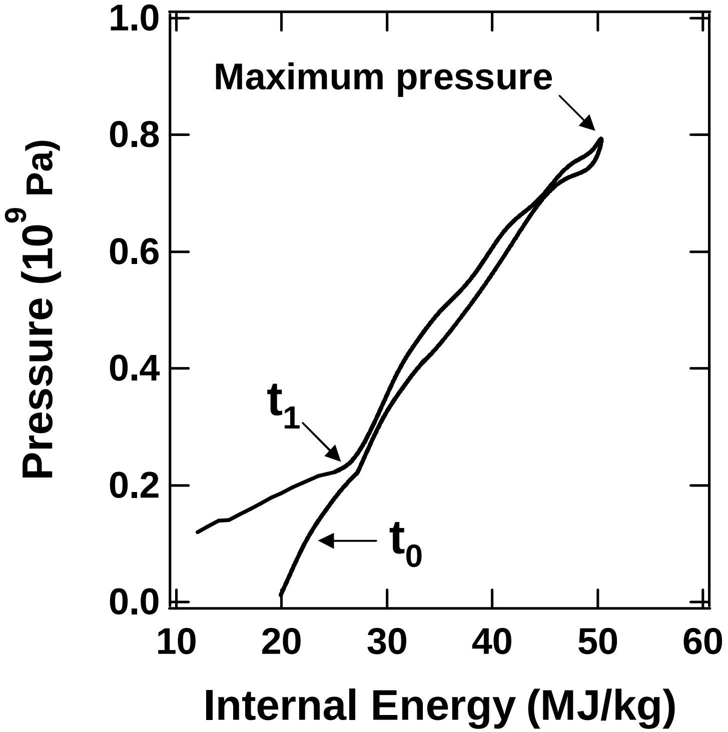
The plasma is heated during more than 200 ps

Interpretation of the measured data in terms of state variables is meaningful only when the plasma is homogeneous (between t_0 en t_1)

Thermodynamic path



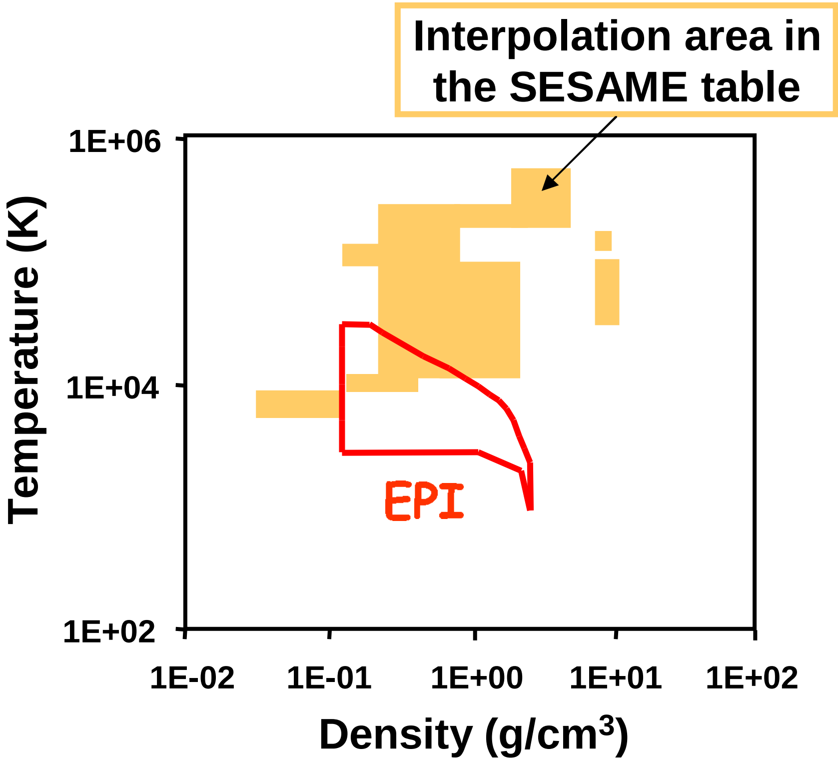
Al plasma at 0.1 g/cm³



Renaudin *et al.*, Phys. Rev. Lett. 91 (2003)

Achieved thermodynamic regime in EPI

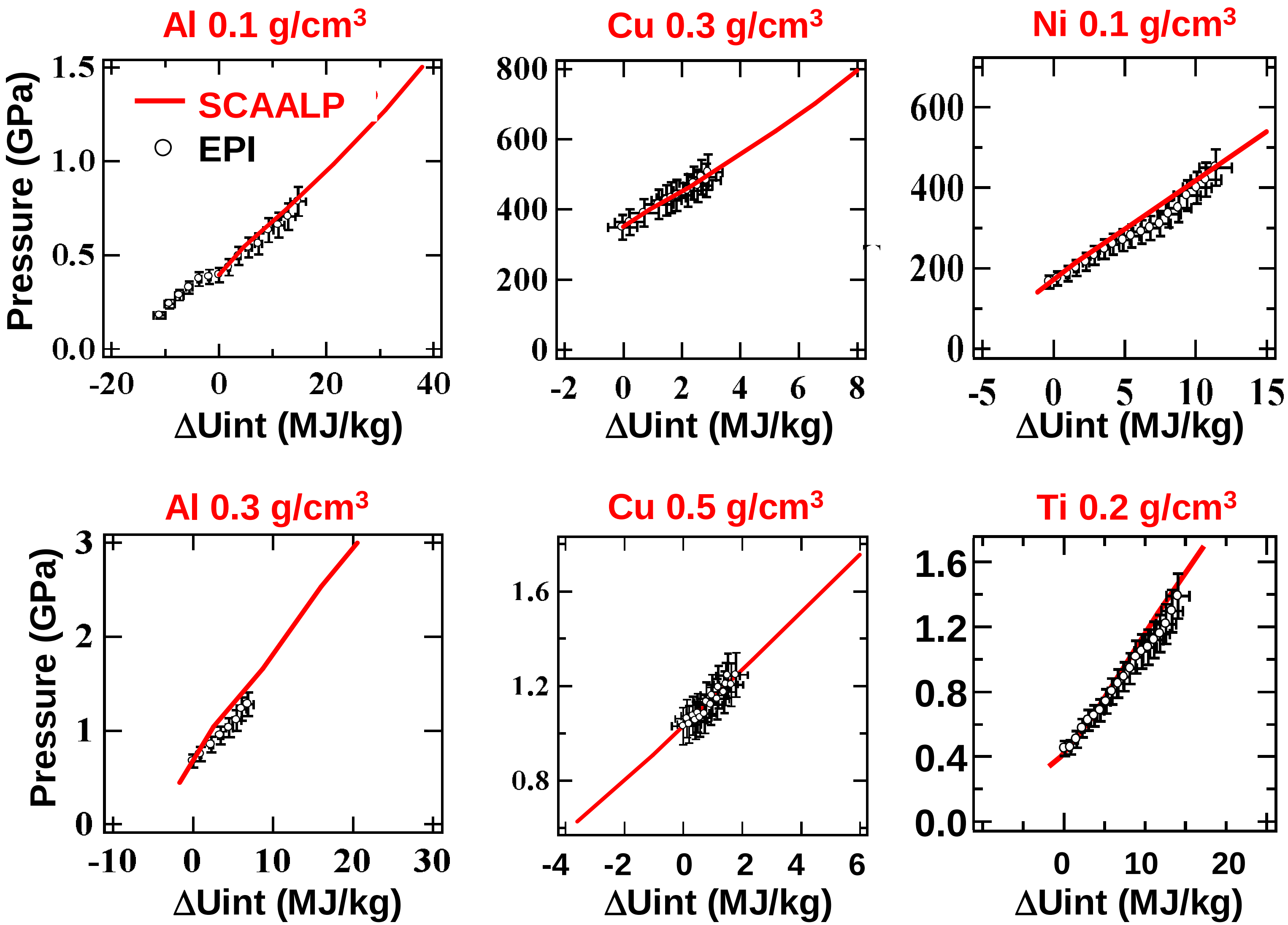
Aluminum



- **Minimal density**: ablation of the EPI walls
- **Maximal temperature**: equilibrium between the electrical power and the radiated power
- **Maximal pressure**
- **Maximal density**: ratio between the sample compressibility and the vessel's rigidity
- **Minimal pressure**: saturation pressure

Lyon & Johnson, *Handbook of the SESAME EOS Library*
Report No. LA-CP-98-100

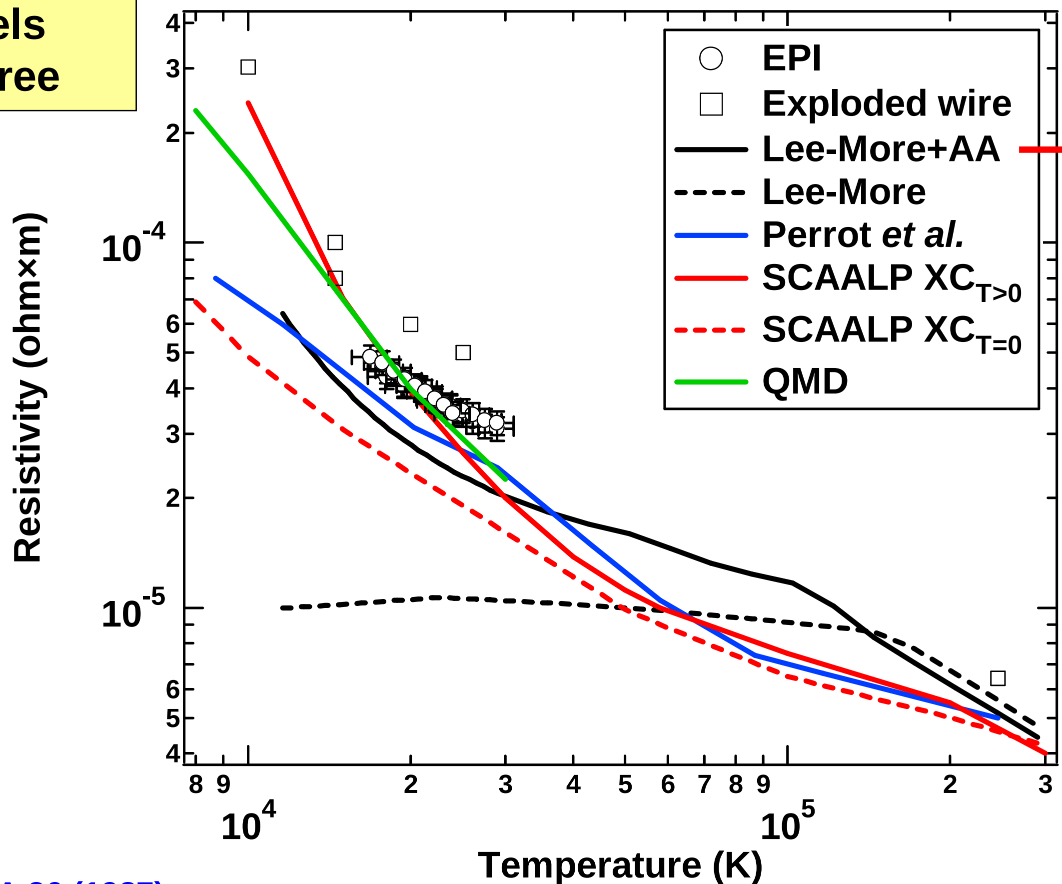
Models developed in the framework of the DFT agree well with WDM EOS data measured in EPI



SCAALP: Blancard & Faussurier, Phys. Rev. E 69 (2004)

Electrical resistivity of aluminum at 0.1 g/cm^3

Low-Te
Models disagree



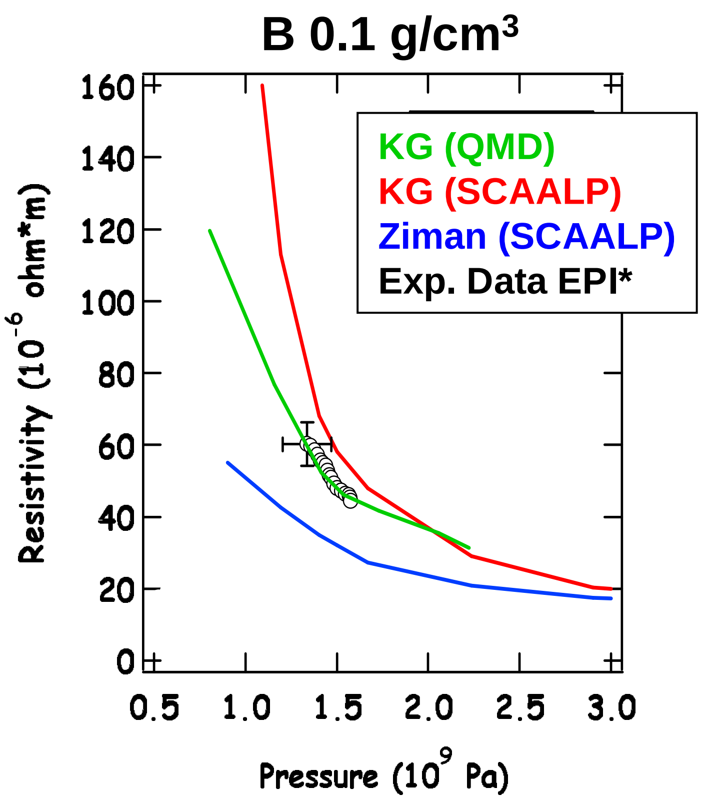
or modified LM formula by Desjarlais, Contrib. Plasm. Phys. 41 (2001)

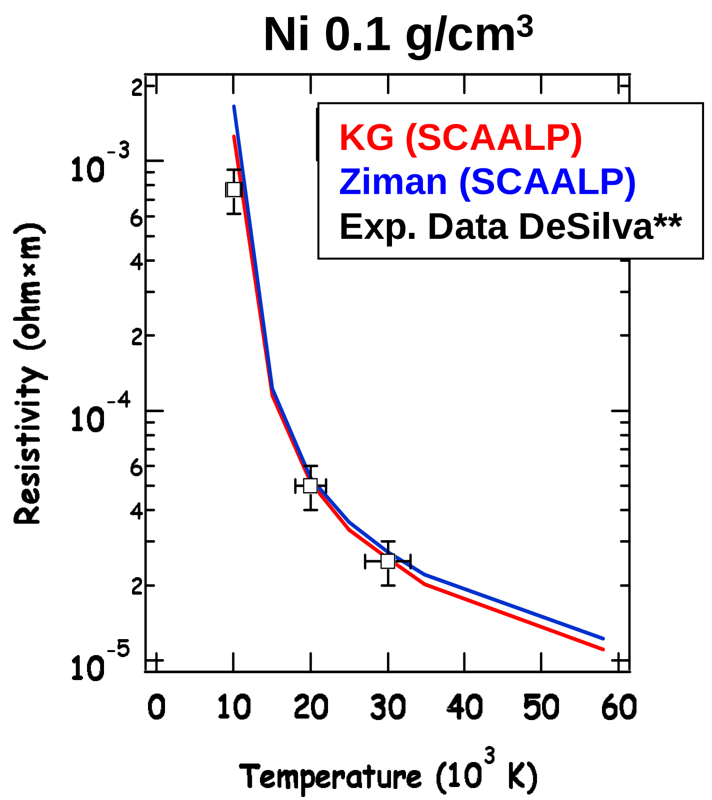
High-Te
Treatment of exchange-correlation and ion-ion interaction have a weak influence

Perrot *et al*., Phys. Rev. A 36 (1987)
Desjarlais *et al*., Phys. Rev. 66 (2002)
Benage *et al*., Phys. Rev. Lett. 83 (1999)
DeSilva *et al*., Phys. Rev. E 57 (1998)
Krisch *et al*., Phys. Rev. E 58 (1998)

Renaudin *et al*., Phys. Rev. Lett. 88 (2002)

Ziman and Kubo-Greenwood formula for DC conductivity give the same results for Al and Ni but not for boron





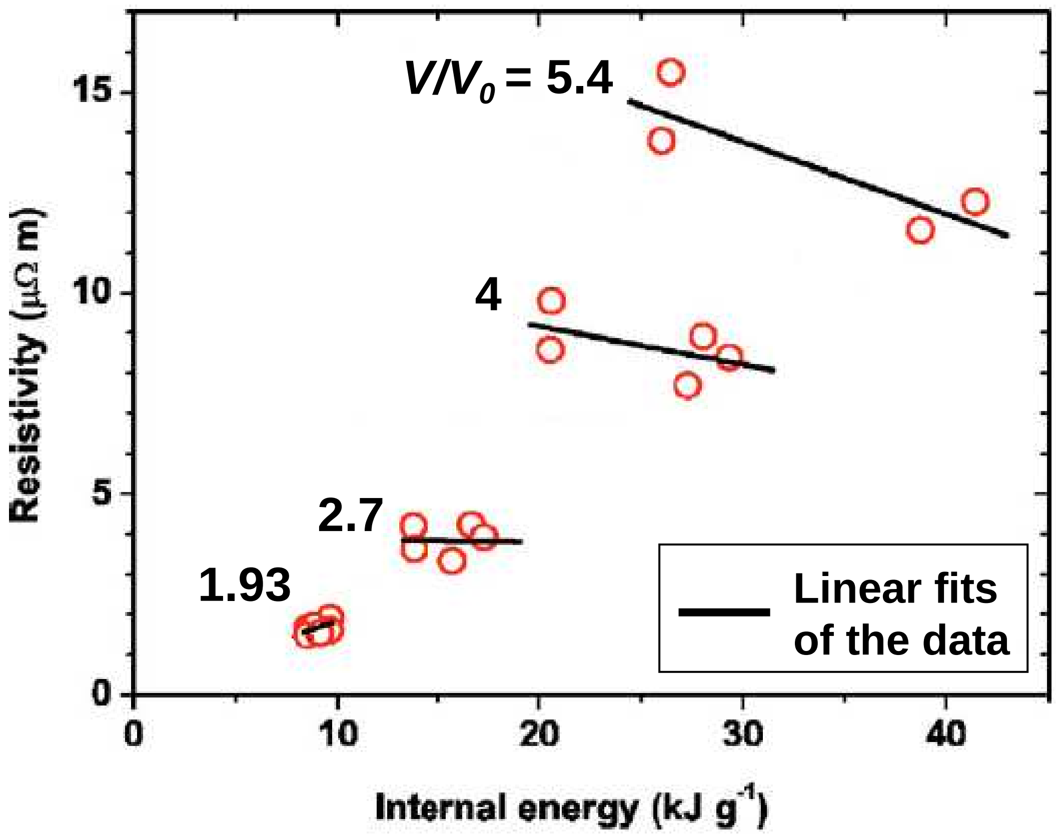
In the thermodynamic regime of the experiments atomic-scale conditions influence strongly the DC conductivity calculations

* Clérouin *et al.*, to be published

** DeSilva and Katsouros, J. Phys. IV 10, 209 (2000)

Experimental data and QMD simulations span the metal-non metal transition

Korobenko experimental results on Al

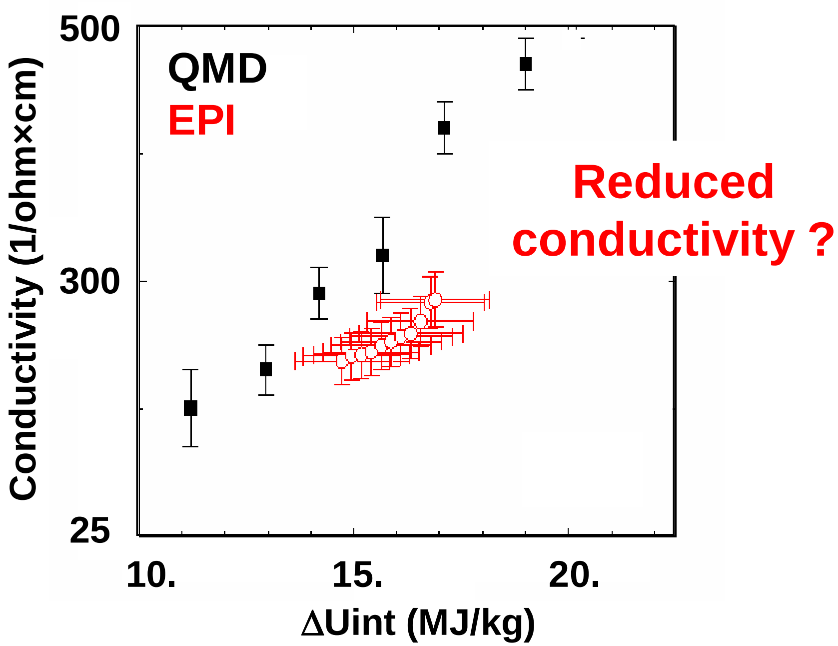


- **Change of sign in slope of the dependence of the resistivity on U_{int}**
- **At 1 g/cm^3 the resistivity is nearly constant**
- **Indication of the transition of aluminum into a non-metallic state ?**
- **Similar behavior for expanded liquid Al was predicted by QMD calculations**
  Desjarlais *et al*., Phys. Rev. E 66 (2002)

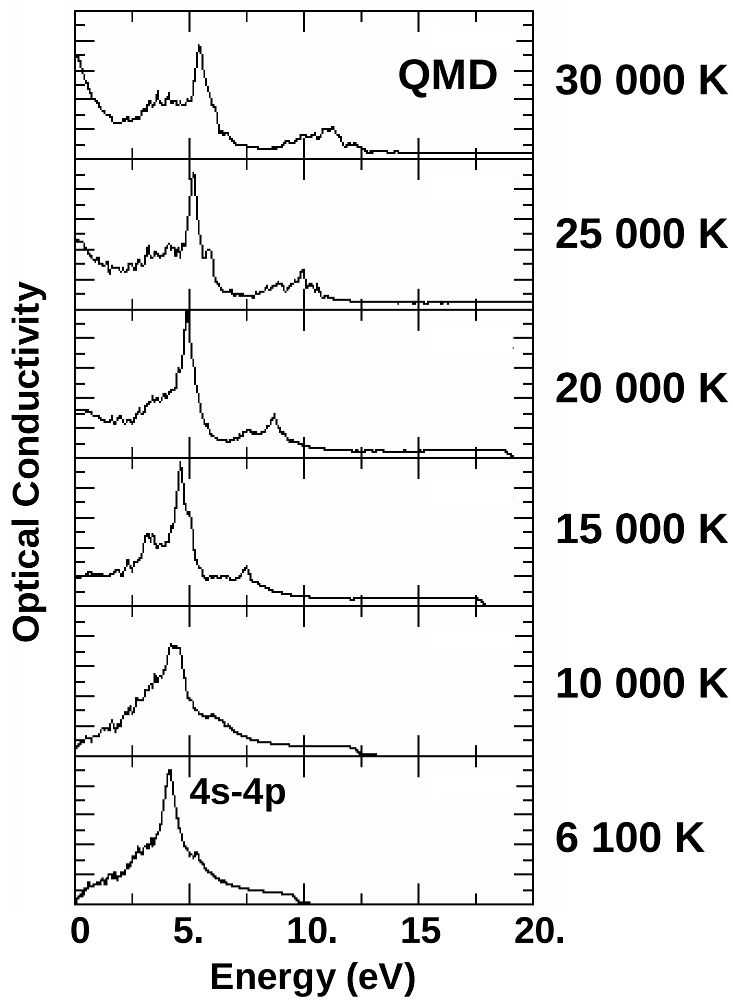
Such a transition appears to be continuous at pressure above 1.5 GPa

Korobenko *et al*., Phys. Rev. B 75 (2007)

Plasma optical properties are sensitive to atomic-scale plasma conditions



Copper at 0.5 g/cm³

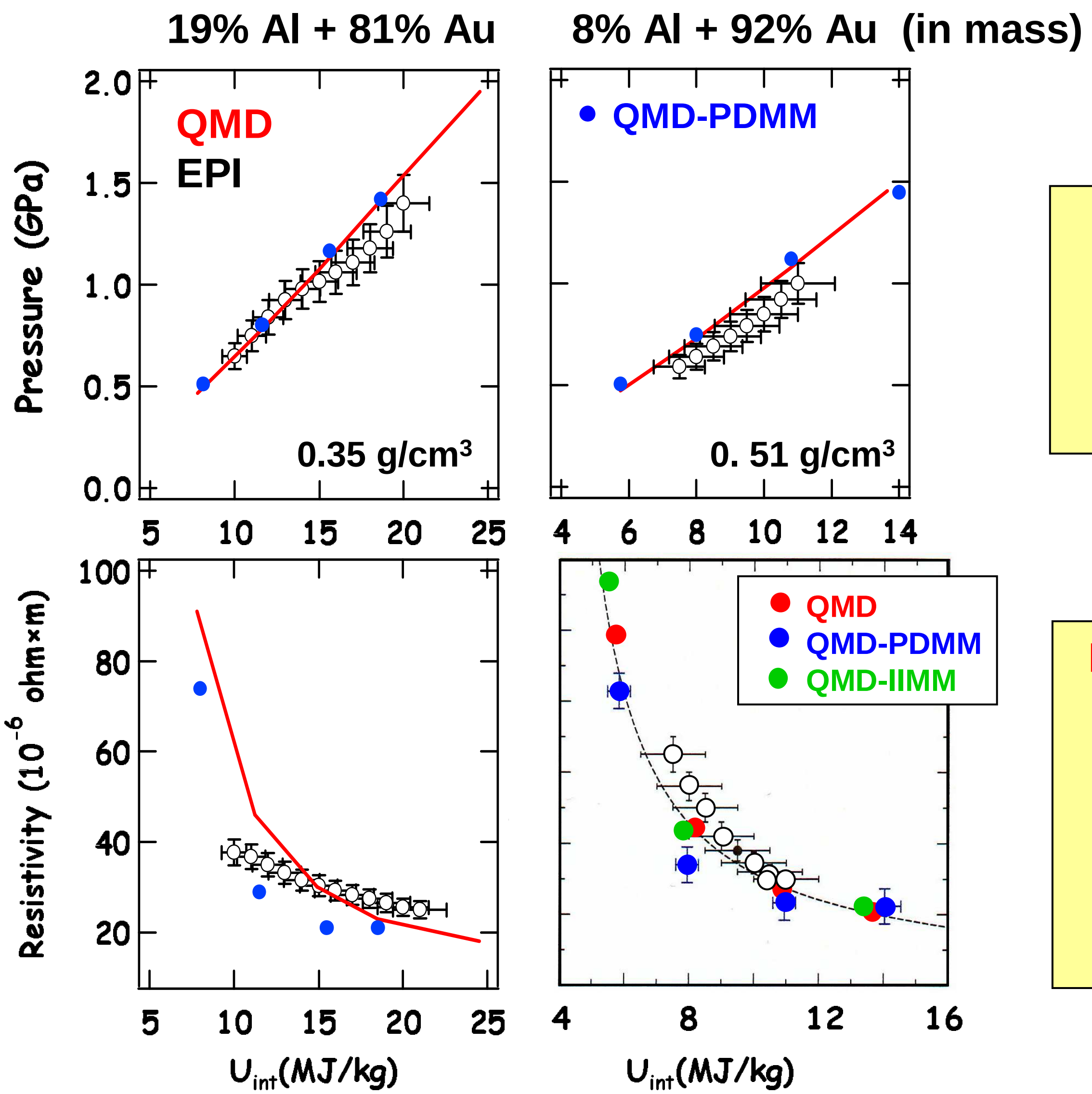


The optical conductivity must be computed using both the Drude model and the atomic polarizability: superposition of a Drude central peak with a few isolated peaks

Dielectric function $\epsilon(\omega) = 1 + 4\pi n_a \alpha(\omega) + \frac{4\pi i \sigma(\omega)}{\omega}$

Clérouin *et al.*, Phys. Rev. B 71 (2005)

Experimental data of Al-Au mixture allow to test some mixing models



QMD simulations are in good agreement with the experimental data and the sum of the partial pressures

Electrical conductivities calculated with an isothermal-isobaric mixing model are in good agreement with the results of direct simulation

Clérouin *et al.*, Phys. Rev. B 76 (2007)

Conclusion

- **Electrically driven warm dense matter experiments is an active field of research**
  - **Various experimental approaches are investigated in several locations**
  - **Measurements are compared and discussed in detail (experimental technique, error bars, assumptions of equilibrium or homogeneity, …)**
- **The thermodynamic regime experimentally explored allows to study 3D and quantum mechanical effects which are challenging to simulate**
- **Quantum molecular dynamics simulations seem to be in good agreement with experimental data (JIHT and CEA)**
- **Experimental perspectives**
  - **At low Te: metal-non metal transition & saturation curves**
  - **At high Te: bound state description**